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13. ABSTRACT (Maximum 200 words) This program examined the feasibility of providing small-scale propulsion systems to provide power and propulsion assistance for soldiers, offering capability for extended vertical leap with heavy combat weights. The concept utilizes multiple small-scale (though not micro) gas turbine engines, capable of providing thrust levels in the 50-lb range, with engine weights of ~5 lbs. The concept uses these engines to help soldiers jump over an obstacle, or possibly to produce electrical power with the efficiency of a gas turbine engine. Analysis, testing, and design of a benchmark propulsion pack was performed, culminating in the development of prototype hardware with gas turbine engines mounted, powered, and coordinated. Various issues related to their starting and operational characteristics of these engines were explored, as well as practical operational issues associated with their use in a backpack configuration, including acoustic signature, heating, etc. Practical issues of engine mounting, starting of multiple engines, and body mounting of the engines were explored. A detailed analysis of these engines, and the general class of small-scale power systems, was conducted to determine their suitability in providing power generation in addition to propulsion. Emphasis was placed on power generation as a secondary function from a system optimized for propulsion performance. Final results produced a four-engine design which, when fully fueled had total weight of approximately 65lbs., producing thrust to 160 lbs. Extreme acoustic signature, highly non-linear thrust profiles, and hot exhaust issues were identified as clear difficulties remaining in the final design.			
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SMALL SCALE PROPULSION FOR JUMP AUGMENTATION

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Abstract

This program was an examination of the feasibility of providing small-scale propulsion systems to provide power and propulsion assistance for soldiers, especially to offer a capability for extended vertical leap with heavy combat weights. The concept under development was the use of multiple small-scale (though not micro) gas turbine engines, capable of providing thrust levels in the 50-lb range, with engine weights of ~5 lbs. The concept was to use these engines to help a soldier jump over an obstacle, or possibly to produce electrical power with the efficiency of a gas turbine engine.

Work on this project proceeded along two tracks. First, the analysis, testing, and design of a benchmark propulsion pack was performed, culminating in the development of prototype hardware with gas turbine engines mounted, powered, and coordinated. Various issues related to their starting and operational characteristics of these engines were explored, as well as practical operational issues associated with their use in a

backpack configuration, including acoustic signature, heating, etc. In the final phase, since the last interim report, practical issues of engine mounting, starting of multiple engines, and body mounting of the engines were explored.

As a second task, a detailed analysis of these engines, and the general class of small-scale power systems, was conducted to determine their suitability in providing power generation in addition to propulsion. In this work, emphasis was placed on power generation as a secondary function from a system optimized for propulsion performance.

Scaling studies of Otto and Brayton cycle engines have been performed to determine the optimum power generating configuration for producing power in the range of a few kilowatts. Trade studies were performed between various propulsion systems to determine the minimum propulsion pack weights attainable. Jumping ability of a soldier using the pack was estimated based on human kinesiological factors and propulsion pack thrust-to-weight ratio. Results indicate that the gas turbine still holds the most promise of simultaneously fulfilling these goals although the power requirement variation between jumping (approximately 200 kW) and electricity generation (approximately 2 kW) ultimately led to the conclusion that the efficient use of one size engine for both purposes is only marginally feasible.

Final results produced a four-engine design which, when fully fueled, with had total weight of approximately 65lbs., producing thrust of up to 160 lbs. Extreme acoustic signature, highly non-linear thrust profiles, and hot exhaust issues were identified as clear difficulties remaining in the final design.

Introduction

Sustained flight with a light-weight, compact jet- or rocket-powered has been pursued by several development efforts in the past, and was evaluated beginning with the first year's effort. There are numerous practical hurdles to the development of a propulsion pack for sustained individual flight. This study has been examining the significantly more modest, and thus more achievable, goal of providing jump-augmentation capability and electrical power generation. To evaluate this possibility, parametric studies of the ratio of propulsion pack weight to that of a user were conducted with flight endurance (time of flight), engine thrust to weight ratio, T/W , specific impulse I_{sp} , and pack structural weight, W , as variables. Additionally, anthropometric and kinesiological factors were researched to determine the jump heights that could be achieved by an average soldier when using a pack that produced less thrust than the weight of the total system, including operator and engine. Work has also proceeded on a rudimentary gas-turbine based prototype pack, under design to test the results of these studies.

The feasibility of using a jet pack for power generation, especially when the engine is in an idle mode, was also explored during this reporting period. In this way, the jet pack is operating as a Brayton-cycle power system, albeit without the technical challenges and poor efficiencies associated with micro-scale turbine engines. Other heat engine cycles were also studied to provide insight into the scaling properties they possess in terms of power to weight ratio and specific fuel consumption (SFC) and to demonstrate the motivation for using small scale heat engines for on-soldier power applications.

Electrical Power Production

Soldiers are being equipped with increasingly electronic, power consumptive hardware such as communication devices, target designators, and navigation equipment.

With the recent successes these types of combat aides have demonstrated, it is likely that there will be an increased demand to supply light weight, convenient, and rugged power generation devices to soldiers. It is anticipated that a soldier may soon have electrical power requirements in the low kilowatt range. Soldiers currently carry as much as 92 pounds of basic equipment, so there is a strong incentive to utilize light-weight power supplies. A comparison of the energy densities of fuels and batteries leads quickly to the conclusion that a simple and efficient means of converting fuel energy to electricity would provide a weight-optimized solution.

There are a wide range of energy densities available from batteries. A lead-acid battery can provide an energy density of approximately 360 kJ/kg. A Lithium-sulphur dioxide battery has an energy density of approximately 1190 kJ/kg~\cite{crompton}. For comparison, the energy contents of gasoline and kerosene are approximately 44 MJ/kg and 43 MJ/kg respectively~\cite{taylor}. Obviously there is a large advantage to be gained if the energy content of these fuels can be efficiently converted to electrical power. This has in fact been the motivation behind much of the current work in micro-engine systems, but the same energy arguments apply at the larger scale as well.

In addition to weight, other important characteristics include volumetric size, noise, thermal signature, and ease of recharging the system. It was generally acknowledged that heat engines produced acoustic and thermal signatures that make their practical use very limited. In experimental tests, this has been identified as a very significant issue, and possibly a technical "show-stopper."

Since the power system weight is affected by both engine weight and fuel weight, the key parameters reviewed were mass specific power P_{sp} and efficiency (which can be related directly to specific fuel consumption SFC). It was determined that a benchmark should be established using manufacturers' data from actual reciprocating engines. The following plots show efficiency and specific power (with fit lines) as a function of engine mass~\cite{cadou}. The specific power plot shows power density on both a mass (lower data set) and on a volume basis. The data has not been experimentally verified and contains a large degree of scatter. Nonetheless, it does bear out two points: on

average, efficiency falls off significantly as size decreases, and secondly, specific power increases as size decreases. In the calculation of overall system weight, these two trends oppose each other as engine size is varied.

Design Concept

A fairly simple concept, the pack consists of four, AMT AT450 Turbine engines. Two mounted on each side of a bar parallel to the shoulders. Each engine is rated for 45 pounds of thrust at 100% throttle, though actually achieving this figure was problematical, as will be addressed later in the test analysis. The shoulder bar holding the four engines are mounted to a frame derived from a parachute harness. This frame also houses the Engine Control Units (ECU's), fuel pumps and batteries; a set of each is required per engine; and finally a collective fuel tank housing roughly thirty pounds of fuel.



Fig. 1 AMT AT-450 Gas Turbine Engine. Unit length is 13”.

The original structural design included the capability for two-dimensional attitude control via rotation of each pair of engines in unison by linear actuators acting on a crossbar causing a moment about the joint and thus rotation. However for the first pack, that was abandoned in favor of simply constructing a pilot friendly and safe pack, as well as starting four separate turbines either simultaneously, or in rapid succession. In

consequence, the same engine mounts were used such that if at some point in the future actuator control is desired it can be added without major complication, yet for now kinesthetic control would be utilized by simply lock the joints in place preventing any movement. Essentially it is a form of instinctual pilot control, whereby the pilot shifts his body position and weight, hence moving his center of gravity (CG) such that it is offset from the line of action of the engines effectively creating a slight moment and translational movement. Thus to move forward the pilot simply leans forward and pitches his legs backward manipulating his CG so that the line of action for the thrust vector is now no longer normal to the ground but pitched forward slightly, causing a horizontal component of thrust to be created and thus forward motion. Similar actions can be taken for translation in other directions, as well as a slight rotation of the shoulders and dropping one shoulder to induce a rotation about the CG.

Harness & Frame Concept

For the successful implementation of a jet pack system, two entirely different load paths must function in unison.

At most times, with the engines throttled down, the frame pack will be supporting a load, similar to that of a frame pack for backpacking. Extensive research into backpack frames found a number of commercially-available packs capable of comfortably holding between forty and eighty pounds of gear supported by a frame which transmits the load vertically down to the hips. Hip support provides is offered for comfort of the wearer, as loads exceeding about twenty pounds become uncomfortable, sometimes painful, and hard to control when supported entirely by the shoulders. The hips however can bear loads in excess of seventy pounds for extended periods of time relatively comfortably and easily controlled during any movement. Thus for the jet pack design, which will weigh approximately sixty to seventy pounds fully fueled, it was decided that the frame must allow for transmission of weight load to the hips of the pilot while in an idle state in

which the pilot supports the weight of the pack. If ultimately incorporated into more extensive battle armor, the frame implementation might of course be modified.

During flight conditions the suspended weight of the pilot must be supported, thus a harness similar to that of a conventional sport parachuting rig was explored. Climbing harnesses were examined but rejected due to the fact they are designed with frontal loading in mind, meaning that the harness is cut such that it is functional when the suspended weight of the climber is supported from the front of the harness (the rope attaches at point near where a belt buckle would be). This is not acceptable since the load of the pack and the line of action of the thrust vector will be down the user's back. However the harness system on a sport parachuting rig is designed to support the weight of the pilot from leg straps, transmitting the load vertically to the shoulders, which is very similar to the desired flight condition of the jetpack. The only difference is that the crossbeam supporting the engine mounts crosses the shoulders approximately two inches further back, which is a manageable situation in terms of construction and load bearing.

As the harness would be an integral part of the jetpack, safety was essential. A vendor was located, Ground Launch Systems, with experience in special parachute harness designs. The company includes an FAA-certified Master Rigger with experience in FAA Technical Standard Order (TSO) requirements for such harness systems.

Throughout the design, weight has been a primary concern. A benchmark target of less than 60 lbs was chosen for the fully-fueled pack, including 30 lbs. For fuel. Initial designs have been in the 80 lb. Range, but with future plans for dramatic weight reduction. First to be modified will be the engine mounts and the solid aluminum I-beam. The engine manufacturer, working with project partner Accurate Automation, has developed a modified version of the ATM that triples thrust with only a doubling of weight. If demonstrated, replacing four engines with two would reduce the pack weight while improving thrust by up to 50%.

With the current design, maximum thrust output with Jet A would be 151 lbs. Even with thrust less than weight, this would double the jump height of an average 180 lb. person. A two-engine design with the advanced designs incorporating a 60 lb. pack weight on a 180 lb. pilot yields a thrust to weight ratio of 1.25, allowing for a stable hover at approximately 75-80% throttle and would offer un-assisted by leg muscle ascent capability

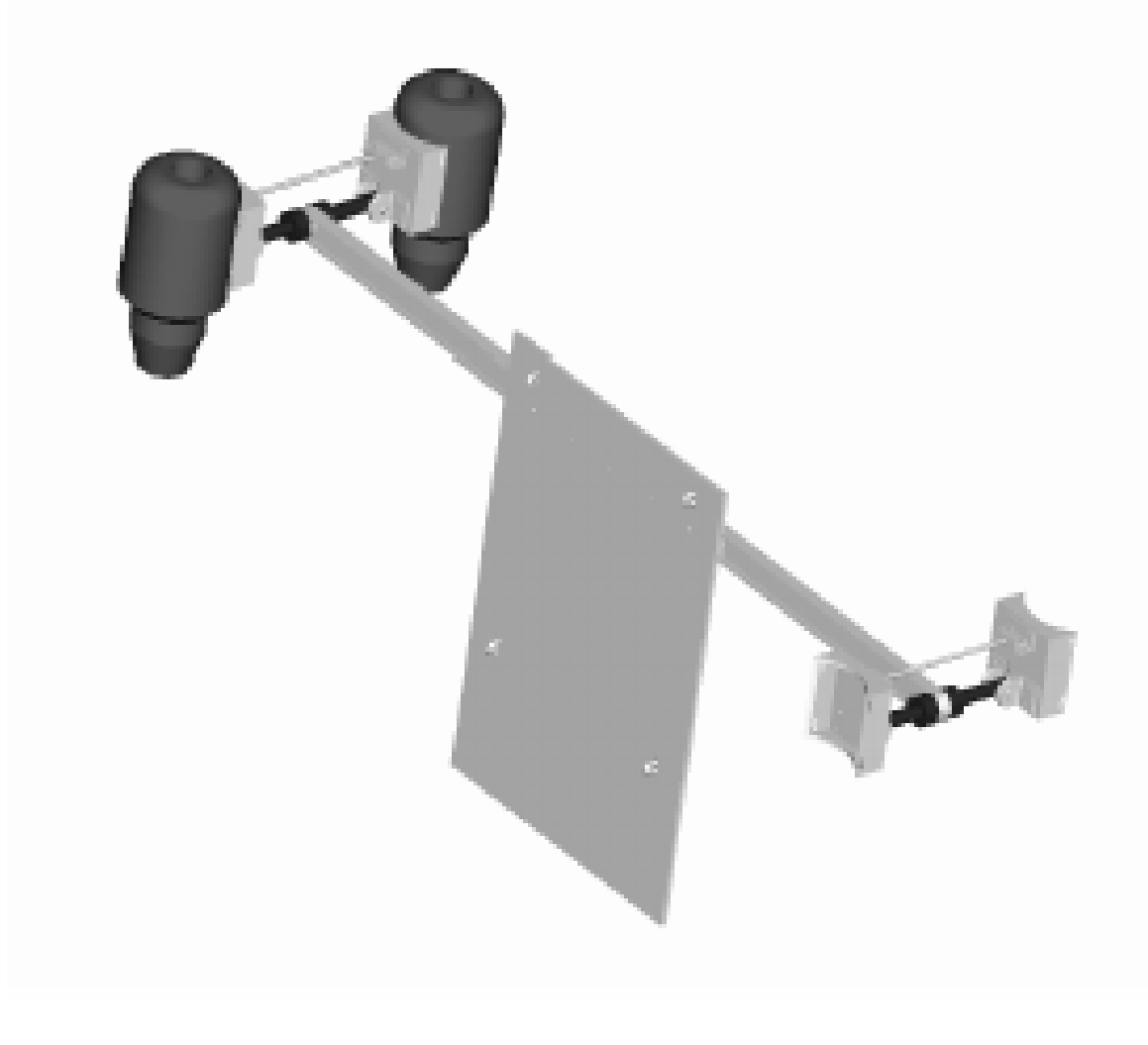


Fig 2. Original concept illustrating the engine mounts and beam construction; right-hand-side is shown with engines mounted, left without. In subsequent design, the solid plate frame was replaced by a lighter tubular aluminum frame.

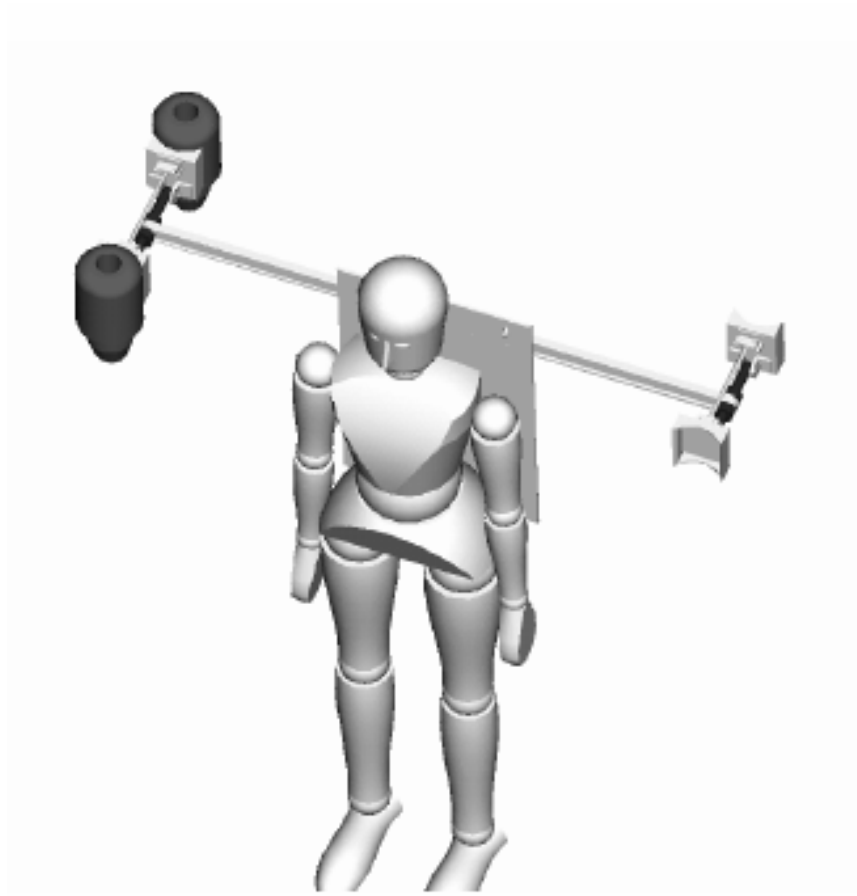


Fig. 3. Backpack mounting on soldier.

Testing & Experimentation

Once each of the four engines was mounted and operated, a series of test runs were performed to establish baseline performance and compare to manufacturer's supplied data.

Fuel Consumption

Engine fuel consumption was measured. Two fuels were tested: commercial aviation jet fuel (Jet A), and kerosene, however after examining the data it became apparent that the differences between the two were negligible with regards to fuel

efficiency. That is to say the engines burned fuel at approximately the same rate regardless of fuel type and thus fuel consumption data was compiled and average consumption values were derived of a conglomerate of data between the two fuels.

Obtaining values for average fuel consumption rates (in pounds of fuel per minute) was important in determining the effective operational range of the jump augmentation system. Final selection of the best operational fuel has not been made, as total onboard fuel requirements and choice of fuel properties will depend on final integrated pack design; a nominal value of approximately thirty pounds of fuel was chosen as a reasonable estimate.

The four-engine assembly of engines was found to burn approximately 5 lbs. of fuel at 100% throttle per minute. At idle they burn approximately 1.25 lbs. of fuel per minute. This would allow for roughly 5 minutes of pack operation at full throttle with a 30lb supply, allowing some margin for priming, start up and engine shut down. If left at idle for the duration, 30 pounds of onboard fuel would suffice for 24 minutes of run-time with all four engines. Idle operation at minimal power, using perhaps only one engine could be extended to up to 90 minutes.

Operationally, full-throttle use would only be employed to augment a jump, and thus the actual time required for full throttle would be on the order of a few minutes. Prior to and succeeding the actual jump, the throttle would remain at idle, thus the total operational time is operationally feasible.

Thrust Measurement

A thrust bench was constructed to directly measure engine performance. The stand was of designed with a maximum thrust load of 300 pounds in mind in order to assure stability during testing. Industrial drawer bearing sliders were utilized to support the weight of the engines and their mountings while allowing 1-D translational movement

parallel to the line of action of the thrust vector. At the end was mounted a load cell in compressive mode to measure the amount for thrust force put out by the AMT450 turbines.



Fig 4. In-line view of the thrust bench showing sliding mechanism, as well as the load cell affixed to the end.



Fig 5. Top view of the load cell.

The engines burn Jet A and kerosene at the same rate; as expected, there is higher thrust (due to the higher energy release rate) from the Jet A. Thrust levels at full throttle are approximately two pounds higher with Jet A. Note that the engines do not deliver the promised 40 lb. Performance from the manufacturer. Table 1 presents the average thrust performance of three of the engines. Note the variation between engines, and also note that each engine performance was affected by ambient conditions, with some repeatability problems for hot engines versus cold-start.

Table 1. Averaged Maximum Engine Thrust Performance

Engine	Jet A	Kerosene
ATM-1	36.9 lbs.	35.6 lbs.
ATM-2	38.4 lbs.	35 lbs.
ATM-3	37.8 lbs	35.4 lbs.
Avg.	37.7 lbs.	35.3 lbs.

There are obvious operational advantages to using Jet-A for a military system. The added thrust (10 lbs. For a 4-engine system) is a notable benefit.

The second observation to note is that which is illustrated by the second to last data point on Attachment 2. The listed thrust measurement is “38.4/39.1” this is due so a slight phenomena that was noticed during testing.

During testing, it was observed that each engine has a throttle lag time that occurs when the throttle is rapidly push to maximum, typical of gas turbine engines. For instance, a maximum thrust measurement was found to be 39.1 lbs, a spike from the steady-state 38.4 lbs. This is a familiar transient that occurs when an the engine has an increase in combustion, with an associated delay time to fight the moment of inertia and increase the rotation rate of the turbine. The thrust spikes slightly above the steady state maximum thrust, generally about 1 lb. higher, because the data from the engine regarding RPM and exhaust temperature are of the previous throttle setting.

Though not very significant, it raises the possibility that the engine controller could be redesigned to deliver a higher impulse on the initiation of the jump, simply by increasing the throttle level faster then the settling time of the engine. This would give a few seconds of higher thrust for the initial part of the jump before the engine settles into its steady state maximum thrust level.

Simultaneous Multiple Engine Testing

The next phase of the project involved simultaneously running two engines at once, the ultimate goal being four simultaneously. This is an operational issue with many practical concerns. Multiple engine startups were attempted by ramping up the number of engines.

To control all four engines simultaneously, a radio controller with eight channels was selected. however specifically it required 4 throttle channels and 4 3-position switch channels. To this end, a custom-designed radio controller system, the Mark22-Bek, was



Fig. 6. Multiple Engine Controller/Transmitter

designed with the Silvertone Corp. The controller has been demonstrated with multiple engines and will eventually enable very streamlined control of all four engines via a master throttle and slave channels.

The thrust bench was re-fitted to accommodate the I-beam cross bar allowing for thrust data collection on two and four engine set-ups, as shown in Fig. 7. As of this writing, tests are planned for the full four-engine configuration. A modified version of the engine stand will be used to conduct vertical 1-D linear motion. Accommodation of a test dummy is also a design consideration for the test stand.



Fig. 7 Thrust stand with I-Beam mounting.

Operations

The following is a list of equipment or materials needed for the start-up of the engines:

- Thrust bench test stand (Load Cell and display meter are fixed to this) with engines on mounts
- Radio control unit and receiver with receiver battery pack
- Fuel tank (should have a minimum of 1 gallon for start up)
- Fire extinguisher for emergencies
- Extension cord to get power from the nearest outlet to the experimental set-up
- Cable ties
- “Start Cart” (the following should be contained on the cart)
 - 1 Electronic Control Unit (ECU) with NiCad battery pack per engine
 - 1 Automatic Start-up Unit (ASU) per engine
 - 1 Engine Data Terminal (EDT) per engine
 - 1 Fuel Pump per engine
 - Compressed air cylinder with regulator (SCUBA type)
 - Propane tank (disposable kind, valve is on cart)
 - 12V car battery

Safety and Environment

At maximum throttle the shaft and turbine blades are spinning at 110,000 rpm, imparting a tremendous amount of rotational kinetic energy. Should the shaft or the blade fail, the steel turbine blades would fly outwards and likely not be contained by the

present shroud design. This has been identified as a significant operational issue. It may ultimately result in the engines being raised above head level on the subject, though that would create some obvious operational inconveniences.

Two other concerns are exhaust temperature and acoustic signature. The measured jet stream from these engines can be felt by humans as far away as 20 m in horizontal mounting. Acoustic output was measured in the 160 db range, with the engines near ear-level. For testing, sound-dampening earphones were used. In the actual operational device, this may be an insurmountable obstacle.